



Standard Operating Procedure 1:

Land Surface Phenology Data Processing Overview for the Southern Colorado Plateau Network

Version SCPN_Landscape_Phenology_SOP1_20200129

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Revision History Log

Version: SCPN_Landscape_Phenology_SOP1_20200129 (original version)

Version number	Section and paragraph	Changes made		Approved by
SCPN_Landscape_Phenology_SOP1_20200129				

Only changes in this specific SOP will be logged here. Beginning with the current version and working back, the version numbers are indicated as a hyperlink to those versions in IRMA. Version numbers are the name of the SOP followed by the date of the revision (see the first line of the table above). The sections and paragraphs affected, a brief description of the changes made, and the person approving the revision are indicated in this table. More detailed descriptions of the changes made and the reason for the changes are provided at the end of this SOP.

Summary

This Standard Operating Procedure (SOP) provides a conceptual overview of the land surface phenology data processing and reporting methods used by the Southern Colorado Plateau Network (SCPN) in the implementation of its satellite-based vegetation condition and phenology, and snow cover extent monitoring protocol (Thoma et al. 2017). It describes the issues and considerations that contributed to decisions about this process, and provides graphical examples of the processing steps and choices. To implement this protocol, staff should be proficient at scripting in Java, R, TSQL, and in using ArcGIS.

For most ground-based monitoring protocols, data are collected using the same methods over time to provide consistent monitoring data. However, for remote sensing monitoring protocols, improvements in data product versions or in processing techniques allow us to change and improve processing methods through time. These changes will be documented in subsequent versions of this SOP

This SOP should provide enough detail to allow a critical assessment of the data handling process. It will explain what is accomplished during processing and why SCPN made individual processing choices. Other SOPs associated with this protocol will provide detailed instructions for data processing.

The SCPN land surface phenology monitoring program uses satellite data from MODIS (Moderate Resolution Imaging Spectroradiometer) sensors on the NASA Aqua and Terra satellites to calculate the Normalized Difference Vegetation Index (NDVI). NDVI is used as a proxy estimate of vegetation greenness within target ecosystems. MODIS data used by SCPN are obtained from the Land Process Distributed Active Archive Center (LP DAAC) as a grid with cell dimensions of ~250 m. The NDVI value for each cell integrates the vegetation signal within that cell area. We process the daily records of MODIS NDVI data by median smoothing the data, and then interpolating missing values. The base products of this process are estimated NDVI values on a daily time-step for cells in target SCPN ecosystems from 2001 to the present day. These base products can be used as maps or as statistics aggregated for target ecosystems. Analysis of these products allows us to examine ecosystem phenology and to estimate daily, seasonal, and interannual changes in vegetation productivity.

While monitoring snow cover extent and duration is also a goal of this protocol (Thoma et al. 2017), it will be addressed in a future phase of the phenology monitoring program.

Abbreviations

General abbreviations

LP DAAC	Land Processes Distributed Active Archive Center
MODIS	Moderate Resolution Imaging Spectrometer
NASA	National Aeronautics and Space Administration
NDVI	Normalized Difference Vegetation Index
SCPN	Southern Colorado Plateau Network
SOP	Standard Operating Procedure
USGS	U.S. Geological Survey

Park Units

AZRU	Aztec Ruins National Monument
BAND	Bandelier National Monument
CACH	Canyon de Chelly National Monument
CHCU	Chaco Culture National Historical Park
ELMA	El Malpais National Monument
ELMO	El Morro National Monument
GLCA	Glen Canyon National Recreation Area
GRCA	Grand Canyon National Park
HUTR	Hubbell Trading Post National Historic Site
MEVE	Mesa Verde National Park
NAVA	Navajo National Monument
PEFO	Petrified Forest National Park
PETR	Petroglyph National Monument
RABR	Rainbow Bridge National Monument
SAPU	Salinas Pueblo Missions National Monument
SUCR	Sunset Crater Volcano National Monument
WACA	Walnut Canyon National Monument
WUPA	Wupatki National Monument
YUHO	Yucca House National Monument

1 Selecting Satellite Data Sources

SCPN is using daily MODIS satellite data from the Aqua and Terra satellites for vegetation index analyses. For most terrestrial data, there are matching Terra and Aqua products (e.g. MOD09GA and MYD09GA). A variety of products has been published from this data:

- for different purposes
 - studies of vegetation, oceans, or atmosphere dynamics
- with different levels of processing
 - raw reflectance data
 - corrected reflectance data
 - derived vegetation index values
 - combined Aqua-Terra products
- at different spatial compositing scales
 - 250 m, 500 m and 1 km cell sizes
- at different temporal compositing scales
 - daily, 7-day, 8-day, 16-day

1.1 Evaluating trade-offs

In selecting satellite data sources, we considered both what products had been used in other phenological studies, as well as characteristics of SCPN ecosystems. Land surface phenology analyses have used a variety of temporally and spatially aggregated data products and smoothing functions (see Thoma et al. 2017 for details). Initially, phenological studies focused on more mesic ecosystems, whether agricultural or natural. While mesic ecosystems often have consistent phenological patterns from year to year, they may have many days of cloud cover, leading to few high-quality satellite observations. Typical mesic system land surface phenology processing has used 16-day aggregate data (e.g. Zhang et al. 2003). These methods would generally assign the aggregate value to the middle of the 16-day period, even though that value could have fallen anywhere within that period. For example, aggregate values from adjacent 16-day time periods could be as little as one day or as much as one month apart. Analyses in mesic ecosystems also typically fit curves to the data (e.g. Soudani et al. 2008), which has limited flexibility to allow for rapid changes or for multiple peaks of greenness during a year.

In contrast, dryland ecosystems, including most SCPN ecosystems, have these characteristics:

- have a large proportion of sunny days, allowing the use of daily data

- can respond relatively quickly to wet and dry weather events
- have variable timing of peaks during the year
- have inconsistent peak amplitudes from year to year

The rapid, inconsistent behavior of dryland ecosystems (Reed et al. 1994), though, increases the difficulty of assigning appropriate curve fitting parameters. Using 16-day data would also reduce our ability to detect shifts in phenological timing. In addition, the southwestern United States is characterized by an early summer drought in the months of May and June that creates high water stress for plants. Climate change is causing warming throughout the year, leading to even earlier seasonal drying of soils during this summer drought (Andrews et al. 2019). Consequently, the early summer drought is expected to expand in time and to be more severe. Increased water stress and increased temperatures are projected to drive changes in plant communities in SCPN park units (Gremer et al. 2018) as well as changes in timing and amount of plant growth, which may create stresses for animal communities that depend on vegetation resources during the spring reproductive and migratory seasons. We use daily MODIS data because it increases our ability to detect shifts in the timing, amplitude, and length of this early summer drought and to test climate-vegetation response projections.

1.2 MODIS products selected

In order to get corrected data with highest temporal and spatial resolution, we are using these two daily MODIS products:

- **MOD09GQ** (Terra) and **MYD09GQ** (Aqua) for NDVI calculation from the red and near-infrared bands. These data are available at a daily timestep for each satellite at ~ 250 m cell size.
- **MOD09GA** (Terra) and **MYD09GA** (Aqua) to filter the NDVI data to retain only the highest quality values. These data are available at a daily timestep for each satellite at a 500 m cell size.

The source NDVI reflectance bands (red and near infrared) have been processed to the stage 3 validation level. This is the highest validation level available for MODIS products. LP DAAC (2003) provides this information about the validation process:

- Product uncertainties are well defined over a range of representative conditions.
- Products are ready for use in scientific publications, and by other agencies.
- There may be later improved versions.
- There are three validation stages:

- **Stage 1 Validation:** Product accuracy has been estimated using a small number of independent measurements obtained from selected locations and time periods and ground-truth/field program effort.
- **Stage 2 Validation:** Product accuracy has been assessed over a widely distributed set of locations and time periods via several ground-truth and validation efforts.
- **Stage 3 Validation:** Product accuracy has been assessed, and the uncertainties in the product well established via independent measurements in a systematic and statistically robust way, representing global conditions.

1.3 Alternative data products

MODIS offers multiple data products that have tradeoffs in their utility (Table 1.1). In the future, SCPN may switch to the combined MCD43A4, or similar product, if current problems with inadequate winter snow screening within that product can be addressed (see section 3.1).

Table 1.1. Example of four MODIS products considered by SCPN that have tradeoffs in utility. The first row (bold) under the header row is the product SCPN is currently using. Snow screening issues are described in section 3.1

MODIS product Terra version	MODIS product Aqua version	Theoretical temporal resolution (days)*	Adequate snow screening	Adjustment for sun/sensor angle effects
MOD09GQ	MYD09GQ	1	YES when combined with median smooth	Partial
eMODIS-Terra	eMODIS-Aqua	7	NO	Partial
MOD13Q1	MYD13Q1	16	NO	Partial
MCD43A4 – combined Aqua-Terra product	MCD43A4 – combined Aqua- Terra product	Daily data modeled using 16- day window	NO	Best**

*Using both Aqua and Terra sources could double temporal resolution; however, all sources are subject to missing values due to cloud/atmospheric effects and snow cover.

** Although it has the best sun/sensor adjustment, the MCD43A4 product still includes problematic sun angle signals in woodland systems, such as pinyon-juniper woodlands discussed in section 3.2.

2 Process Steps

The following steps broadly describe SCPN's download, processing, and initial data analysis of MODIS land surface phenology data. For each of these steps we, also build into the scripts and into

the detailed SOPs the process documentation, metadata download, automation, data backup, data archiving, and quality control checks.

2.1 Identify target MODIS cells. Tool: ArcGIS

We identify an individual MODIS cell by the latitude and longitude of the cell center (see section 4 for more detail). MODIS cell centers do not shift through time; therefore, we typically identify target cells only once. Steps involved are

- Select target cells in upland ecosystems either by using inference frames from ecosystems that are part of SCPN's ground-based integrated upland monitoring program, or by using the SSURGO soil map data (NRCS 2019) corresponding to those ecosystems. SSURGO data are typically the gridded SSURGO product.
- Select target cells in riparian ecosystems based on visual identification of 'greener' riparian areas in MODIS imagery.

2.2 Download screened MODIS NDVI data. Tool: Google Earth Engine

- Select MODIS-Aqua and MODIS-Terra daily reflectance data at the 250 m cell size for the overall SCPN area (MOD09GQ and MYD09GQ products).
- Quality screen to keep only high-quality reflectance values (section 3).
- Calculate NDVI using the standard NDVI equation:

$$\frac{\text{Near infrared reflectance} - \text{red reflectance}}{\text{Near infrared reflectance} + \text{red reflectance}}$$

- Extract values for the target ecosystem points, export to csv format, and download.
- Extract all version names of the daily MODIS source files as metadata files, and download.

2.3 Smooth and interpolate data for each cell. Tool: R and R-Studio

SCPN chose a 15-day window for median smoothing because it will retain most temporal variability, but still have enough daily values from Aqua and/or Terra to minimize the effect of outliers. The Colorado Plateau has a high proportion of clear days during either the morning (Terra) or afternoon (Aqua) satellite overpasses throughout the growing season to allow this relatively narrow calculation of the median smooth. We use a minimum count threshold of three values within every smoothing window to prevent the inclusion of any single outlier value within that window. If a large number of outlier values are present, the final data will still have artifacts caused by outliers. Steps involved are

- Create a 15-day median smoothed value for each day. This will require a minimum of three high quality values to calculate the median. Days with < 3 values within the 15-day period will have no smoothed value (Figure 1.1).

- Use a linear interpolation to estimate missing values, thereby creating a complete daily time series for each cell.

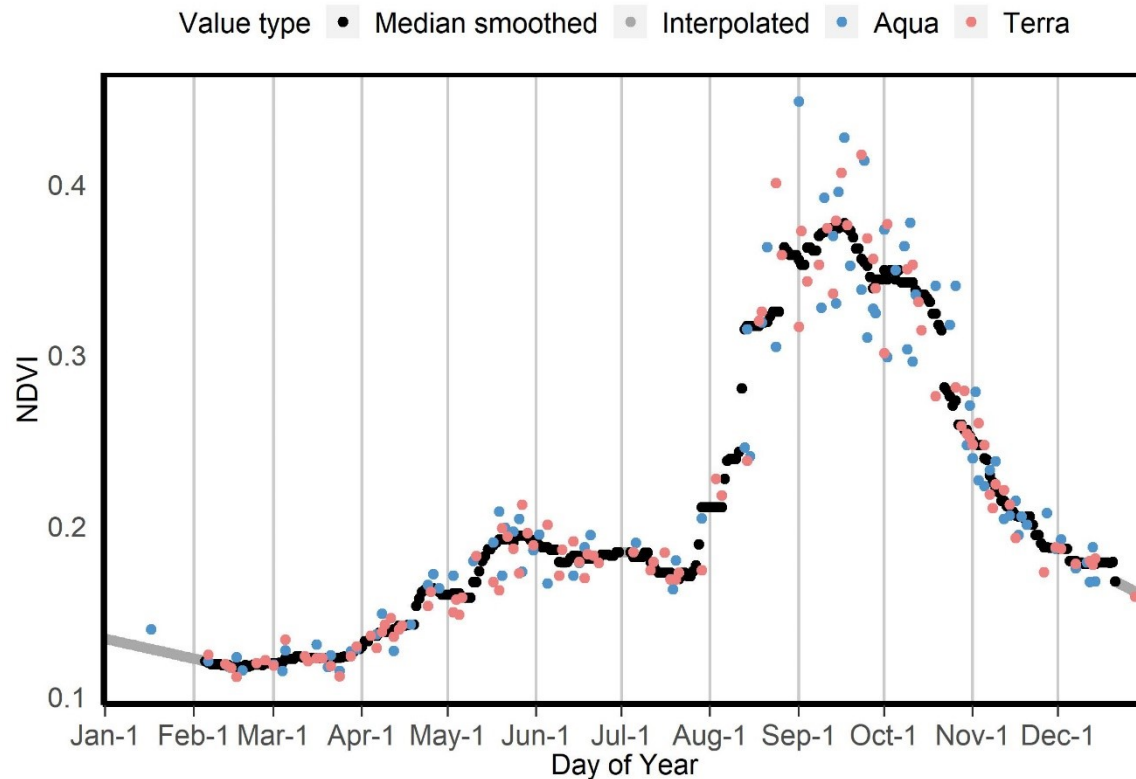


Figure 1.1. Example of how SCPN processed NDVI data for a single MODIS cell in Petrified Forest in 2010. We began with high-quality values from the Aqua (blue dots) and Terra (pink dots) satellites. We median smoothed those data using a 15-day window, keeping only those median values with at least three contributing raw values. We then filled in missing daily values with linear interpolation. The final processed data product consists of the smoothed, interpolated daily values (black and gray dots, respectively)

2.4 Export to SCPN SQL Server database. Tools: R, R-Studio, SQL Server

Export the daily processed data to SQL Server for data storage and archiving. All additional displays and analyses will be done using this dataset.

2.5 Aggregate and report data for each ecosystem. Tools: R and R-Studio

Once the daily data are available, they can be analyzed and displayed in a variety of ways, depending on the project goals. Some examples of likely steps in analysis are

- Calculate aggregate values, typically using percentile values for ecosystems (e.g. median) to avoid the effects of including non-target cells due to errors in source data.

- Display aggregate statistics, including maps of temporal aggregates (e.g. a map of annual peak NDVI for each cell) or graphs of spatial aggregates (e.g. a heat-map of daily ecosystem median values, Figure 1.2).
- Calculate and display combined spatial and temporal aggregates (e.g. annual median peak NDVI for an ecosystem, Figure 1.2, marginal plot).

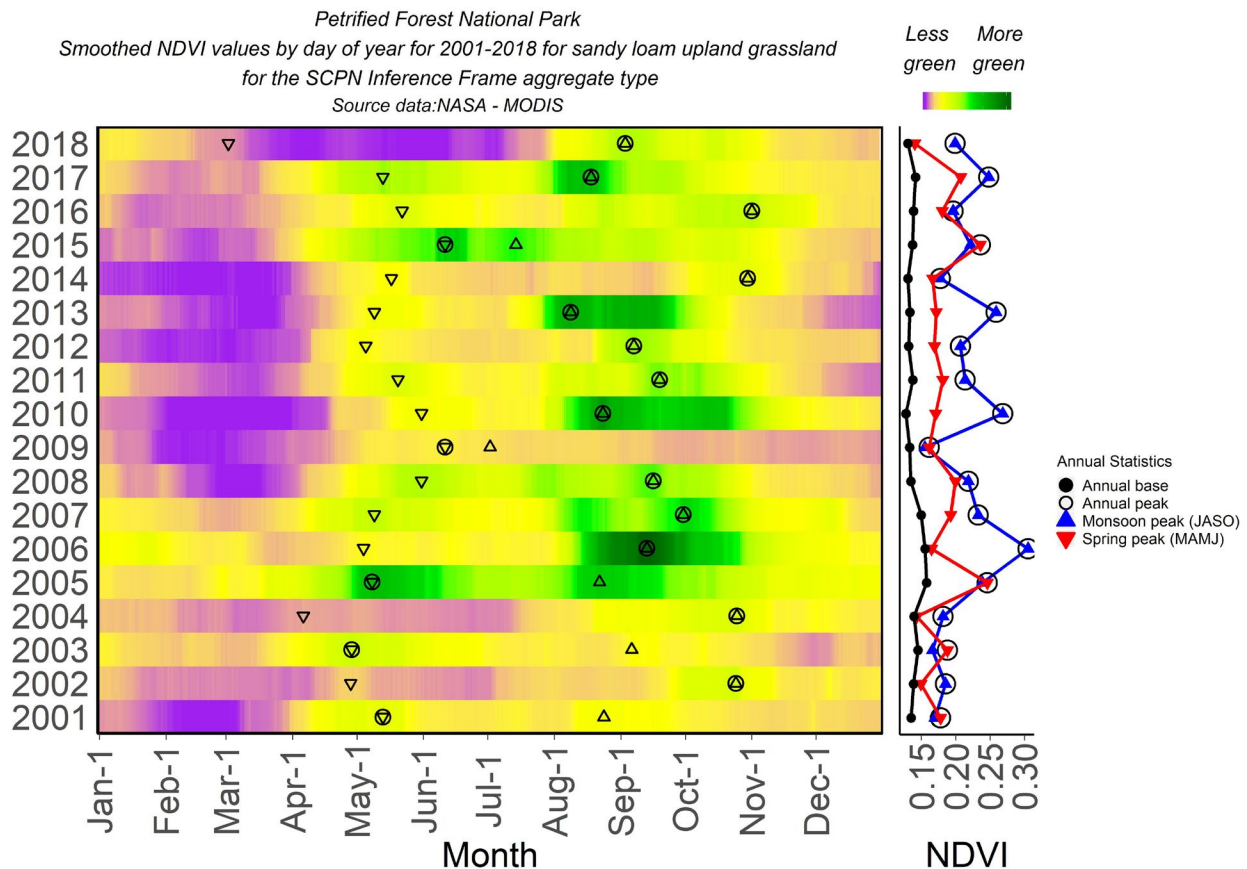


Figure 1.2. Example display of ecosystem-level statistics. This heatmap graphs phenological patterns within the Petrified Forest sandy loam upland ecosystem over a period of 18 years. Symbols on the graph show the timing of seasonal and annual peaks in median ecosystem NDVI. The marginal graph (right) tracks the size of those peaks from year to year, as well as showing the annual minimum NDVI.

3 Data Quality Screening

Satellite data quality screening is designed to remove values that may be poor quality or non-target, due to conditions like snow cover, actively burning fires, temporary flooding, clouds, and poor atmospheric conditions (e.g. dust). SCPN uses the MOD09GA/MYD09GA products for data quality screening. This dataset provides a quality field ('state_1km') for every MODIS cell for every day for each satellite (Aqua and Terra). Within the state_1km field are 11 parameters describing the state of that cell. SCPN retains only NDVI values having the highest possible quality value for each parameter within the state_1km field. This translates to an integer value of 72 (Table 1.2).

Quality screening methods should be reviewed whenever adding new ecosystems to the analysis or changing data sources. Three examples of screening problems encountered in SCPN ecosystems are 1) incomplete winter snow screening, 2) desert aerosol effects, and 3) false winter NDVI peaks in woodlands.

Table 1.2. Individual parameter values for the state_1km value of 72. Parameter values are encoded as 'bits' within the state_1km field. Bit position for MODIS data is calculated from right to left. For more details on using bits to encode quality data for MODIS, see Vermote et al. (2015).

Bit position	Bit value	Parameter	Parameter value
0-1	00	Cloud state	clear
2	0	Cloud shadow	cloud shadow: no
3-5	001	Land/water flag	land
6-7	01	Aerosol quantity	aerosol quantity: low
8-9	00	Cirrus detected	cirrus detected: none
10	0	Internal cloud algorithm flag	cloud flag: no
11	0	Internal fire algorithm flag	fire flag: no
12	0	MOD35 snow/ice flag	snow ice flag: no
13	0	Cell is adjacent to cloud	adjacent to cloud: no
14	0	Salt pan	salt pan flag: no
15	0	Internal snow mask	no snow

3.1 Incomplete winter snow screening

The current quality screening method using the state_1km field described above provides good quality phenological data when combined with median smoothing. Median smoothing (described later in this document) removes the effect of rare outliers while preserving most of the high temporal resolution phenological signal. Previously recommended methods of quality screening (e.g. the original methods developed for SCPN and NCPN, using NDVI_Quality band 3 of the MOD13Q1 product, described in Thoma et al. 2017) did not adequately screen snow-affected values for many forested and woodland ecosystems (Figure 1.3). The resulting low values affected calculations of annual amplitude and effectively masked the interannual variability in annual amplitude. The artificially low values may change start and end of season dates when those dates depend on a threshold or curve response, and are likely to affect the calculation of appropriate thresholds and curves for ecosystems. Problematic low values are most easily detected using either daily or weekly data (Figure 1.3). These have high enough temporal resolution to show that the rapid changes in NDVI are ecologically improbable in the autumn for evergreen systems (except in cases of fire) and similarly improbable in spring for both deciduous and evergreen systems.

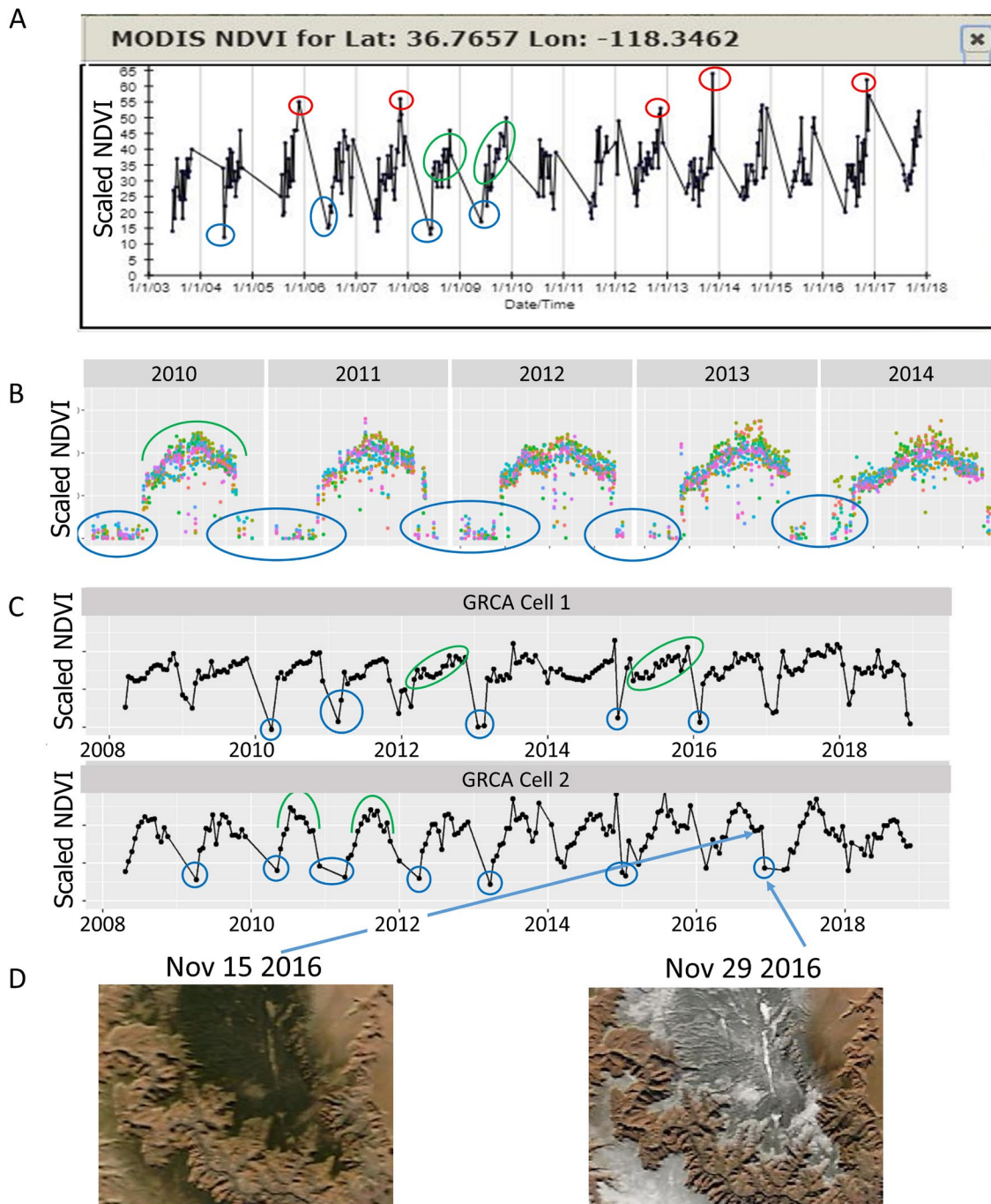


Figure 1.3. Examples of unlikely winter peaks and of inadequate screening of winter snow values using published MODIS screening methods. In panels A, B, and C, blue ellipses identify some ecologically improbable low NDVI values; red circles identify some unrealistically high winter peaks; green ellipses or lines show the general seasonal pattern of NDVI, which in some locations is a realistic summer-peaking curve and in other locations shows a false pattern, increasing towards the winter solstice (*continued*).

Panel A. NDVI profile in a high elevation woodland (3230 m) in the Sierra Nevada mountains of California, obtained using the Forest Threats Assessment Forewarn website (<https://forwarn.forestthreats.org/>). Panel B. NDVI profiles for several mixed conifer cells (color coding indicates individual cells) on the North Rim of the Grand Canyon, obtained using eMODIS (U.S. Geological Survey 2018) Aqua and Terra data that were screened to remove snow values. In this twice-weekly time series, the unrealistically sharp drops and rises are more apparent than in 16-day data. Panel C. NDVI profiles for two locations in mixed conifer forest on the North Rim of the Grand Canyon created using 16-day MODIS Terra data screened following initial NPS Colorado Plateau Network protocol (Thoma et al. 2017). Panel D. MODIS true color images for the dates around one of the winter NDVI drops show the effect of snow on data that have theoretically been screened to remove snow values.

3.2 False winter peaks in woodland ecosystems

As a result of problems identified while developing this protocol, Norris and Walker (in prep) explored winter NDVI peak patterns in some western woodland ecosystems (Figures 1.3 & 1.4) and established that they were false winter peaks, and not driven by vegetation greenness. The false winter peak pattern is particularly strong in pinyon-juniper ecosystems—more than 80% of the annual variability in NDVI in the SCPN-monitored GRCA pinyon juniper ecosystem can be explained by a combination of solar and sensor angles (Norris and Walker, in prep). This suggests that vegetation response plays a small role in the intra-annual NDVI signal. The winter peak pattern also affects ponderosa pine ecosystems, although the strength of that effect has not yet been estimated. Consequently, SCPN is excluding pinyon-juniper and ponderosa pine ecosystems from land surface phenology analyses until a solution to mitigate these effects is found.

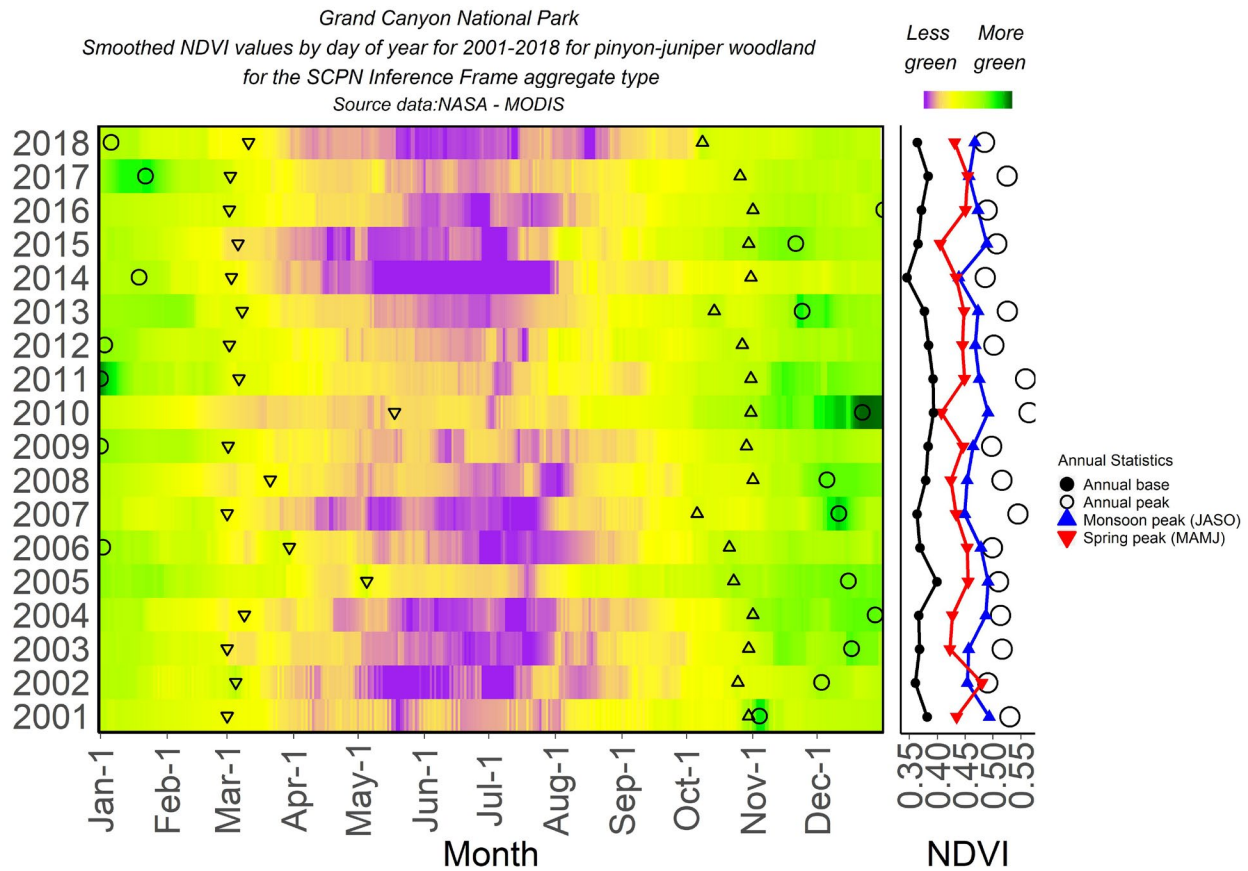


Figure 1.4. Consistent false winter NDVI peaks caused by vegetation structure and solar-sensor angle geometry in the Grand Canyon pinyon juniper ecosystem monitored by SCPN. 15-day median-smoothed NDVI derived from daily MODIS data, following processing methods described in this SOP. *Inference Frame aggregate type* is described in section 4.2.

3.3 Desert aerosol effects

Our quality control examination of samples of data from single cells in each ecosystem has shown that some cell locations have consistently (all years) or erratically (some years) missing high quality values when compared to nearby cells that should have similar atmospheric conditions (Figure 1.5). In the GLCA, PEFO, and WUPA ecosystems, a substantial number of cells have low numbers of high quality values; we refer to these as 'poor record cells'.

Ecosystems in these parks are consistently sunny, and nearby cells often have high numbers of high quality values ('normal record cells'). We further examined a few example cells with this pattern in both ecosystems. When examining the quality parameter values (Table 1.2) for days when nearby cells have good quality, the most common patterns were that the individual state_1km parameter values were identical except for

- The bit indicating aerosol level had a value of either 'average' or 'high' in the 'bad' cells, but had a value of 'low' for a nearby 'good' cell on the same day. It is possible that these are areas subject to high dust levels from a dust source at or upwind of the cell.

- The bit indicating whether a cell was adjacent to clouds had a value of 'yes' in the 'bad' cells, but had a value of 'no' for a nearby 'good' cell on the same day. A small, 2-day check of pixels with 'adjacent to clouds' parameter values showed no visible clouds in the area (western GLCA, May 4th and 5th, 2011).
- Less commonly, the bits representing the land-water parameter had a value of 'ocean coastlines and lake shorelines' or 'ephemeral water', including cells several kilometers away from the high-water shoreline of Lake Powell.

Because the aerosol parameter values of 'average' or 'high' removed many values, we initially considered that the aerosol parameter value requirement of 'low' might be too strict, and so tested a few cells with a more relaxed aerosol parameter value standard of 'low' or 'average'. However, in the small sample we examined, the resulting data had greater noise (short-term variability in NDVI that is not explainable by normal ecological processes) that would have reduced the quality of statistics calculated from the cells.

To mitigate the effects of the poor record (Figure 1.6) from these cells, we screen cells based on their number of high-quality values in the month of June, because this month is consistently sunny across the southwest. To be retained, an individual cell (Table 1.3) must have a minimum of six high-quality June values in every year, and a median count of ten high-quality June values across the 15-year test period (2003–2017). This set of cells should be reviewed approximately every 5 years. The earliest years of the MODIS record were not included in the test period because the Aqua satellite did not provide usable data until July 2002.

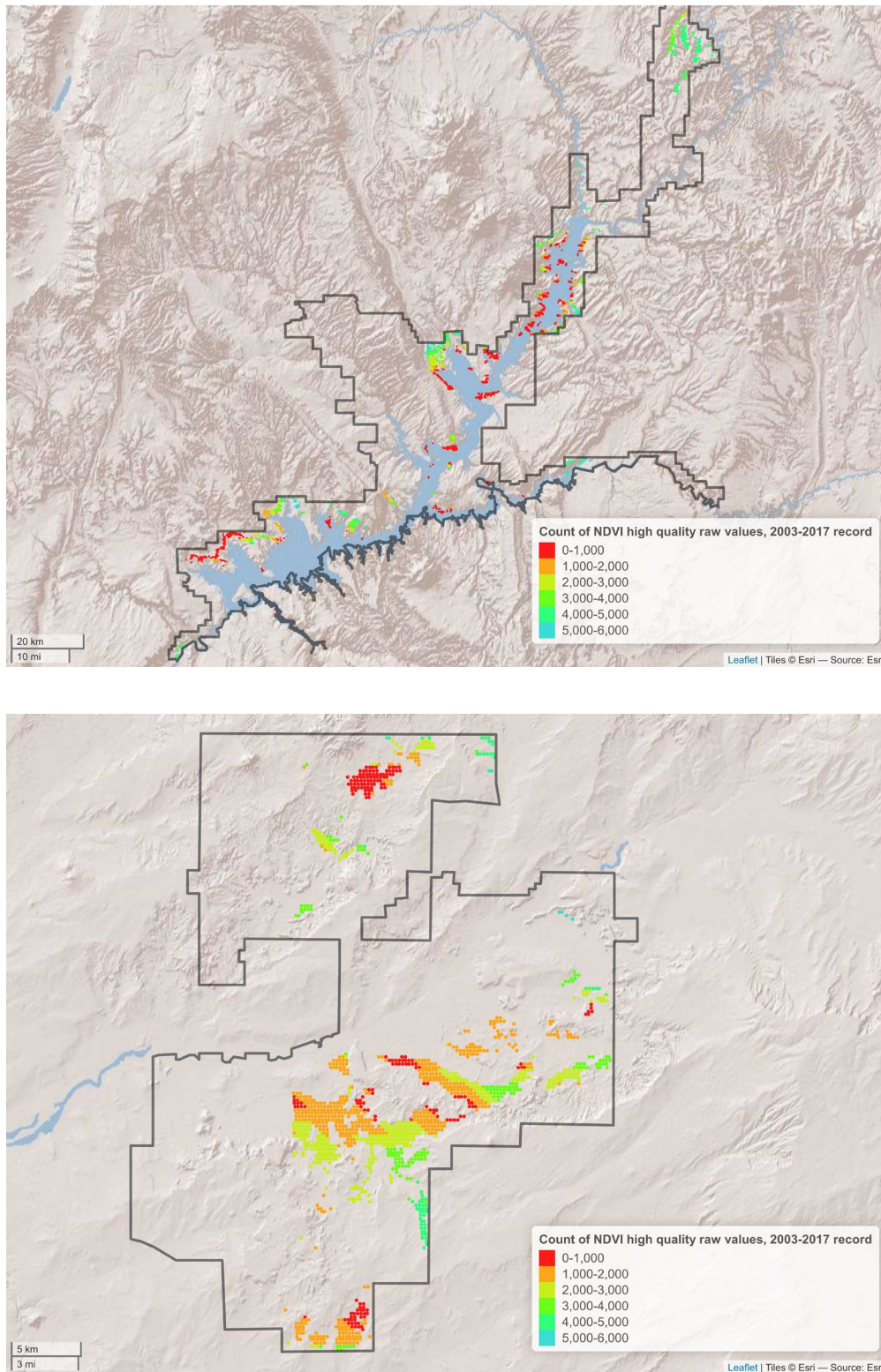


Figure 1.5. Example of the spatial variability in the number of high-quality NDVI values for a 15-year period of record for the desert sand grassland and shrubland ecosystem in Glen Canyon NRA, (top) and clayey fan ecosystem in Petrified Forest NP(bottom). We would expect the counts to be similar across points within the same ecosystem because they share similar climate, but the counts of points are quite

variable. The total number of values possible for this time period, assuming a perfect high quality record, is 10,958.

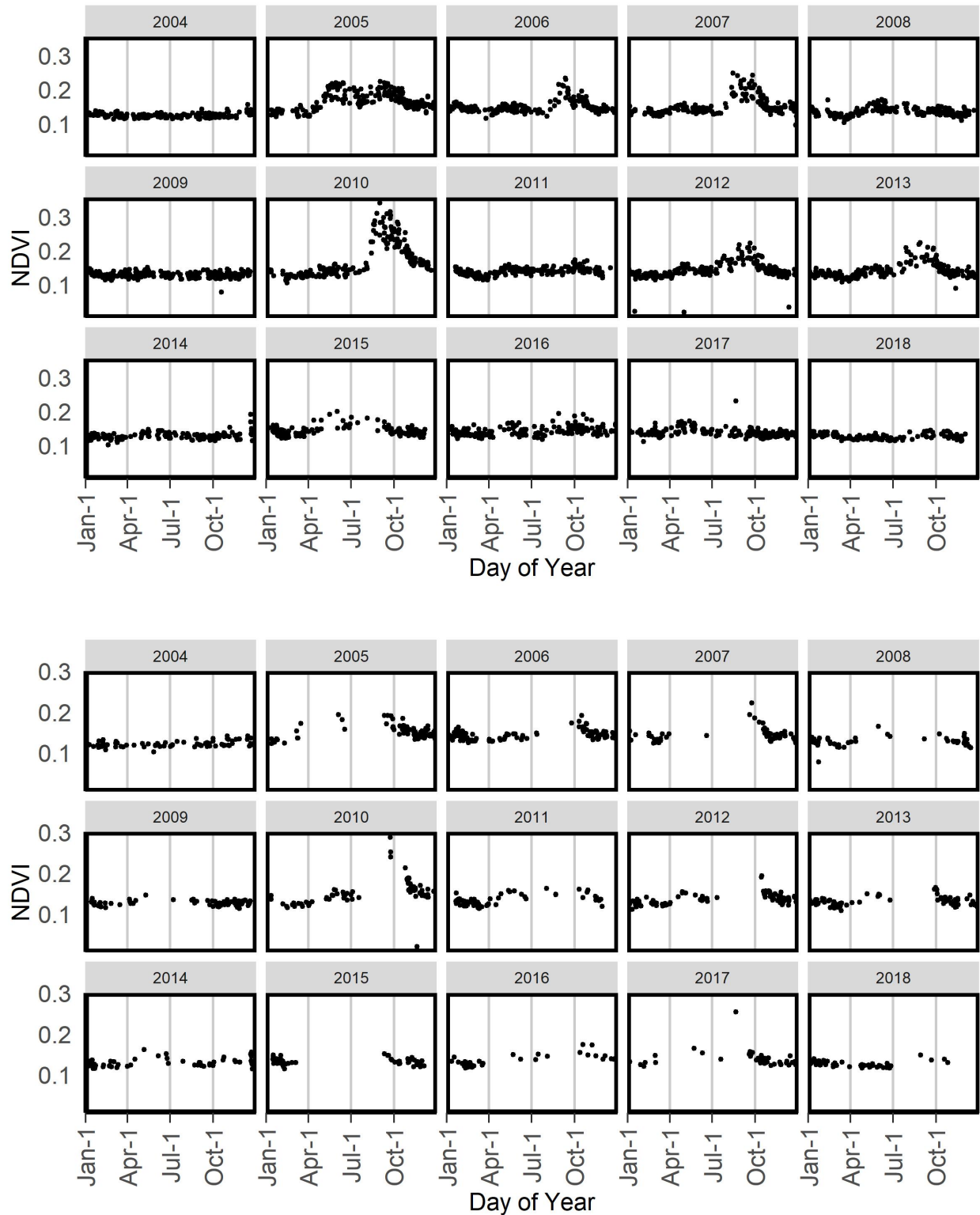


Figure 1.6. Example of raw, high quality MODIS NDVI records from single cells from 2004–2018. Upper panel shows an example from a cell with a good quality record in the Petrified Forest, Clayey Fan ecosystem. Bottom panel shows an example from a cell with a poor record in the same ecosystem, which should have similar cloud cover and atmospheric conditions. Points show high-quality NDVI values from both MODIS-Aqua and MODIS-Terra.

Table 1.3. Total MODIS cell counts for each upland ecosystem and the percent of cells that have poor records, defined in section 3.3 as any cell that does not have a minimum of six high-quality June values in every year, and a median count of at least ten high-quality June values across the 15-year test period (2003–2017). Ecosystems with > 10% poor record cells are highlighted in yellow. Ecosystems with >50% poor record cells are highlighted in red.

Ecosystem ID	Ecosystem name	All cells (count)	Poor record cells (count)
AZRU_A	Limy upland grassland and shrubland	2	0
BAND_P	Mesa-top pinyon-juniper woodland	296	0
CHCU_S	Sandy loam upland grassland and shrubland	247	2
GLCA_A	Desert shallow sandy loam shadscale	2738	1453
GLCA_D	Desert sand grassland and shrubland	507	148
GRCA_M	Mixed conifer forest	1344	0
GRCA_P	Pinyon-juniper woodland	2766	6
MEVE_L	Loamy mesa-top pinyon-juniper woodland	83	0
MEVE_S	Shallow loamy mesa-top pinyon-juniper woodland	25	0
PEFO_C	Clayey fan grassland and shrubland	1363	1142
PEFO_S	Sandy loam upland grassland and shrubland	1367	638
PETR_P	Malpais grassland and shrubland	134	0
WACA_P	Ponderosa pine woodland	47	0
WUPA_L	Volcanic upland grassland and shrubland	241	208
WUPA_S	Loamy upland grassland and shrubland	117	49

4 Selecting Target Cells in SCPN Ecosystems

4.1 Determining the analysis extent and choosing target areas

MODIS phenology information could be used in and/or near every park unit within the SCPN. We are not reporting phenological information for every MODIS cell within each park because of complications in analysis, interpretation, and quality control (described further in section 3). Because of these issues, we instead report initially on a limited number of riparian ecosystems, and on most upland ecosystems previously selected for monitoring by the SCPN Upland vegetation and bird monitoring protocols (Table 1.4).

Table 1.4. List of ecosystems currently monitored as part of the SCPN ground-based upland vegetation monitoring protocol. Some ecosystems also have bird monitoring: **X** indicates bird monitoring for that ecosystem, **C** indicates parks where the two park ecosystems are combined into a single bird monitoring area, – (dash) indicates no bird monitoring in that ecosystem.

Park Code	Ecosystem ID	Ecosystem name	Bird monitoring
AZRU	AZRU_A	Limy upland grassland and shrubland	-
BAND	BAND_P	Mesa-top pinyon-juniper woodland	-
BAND	BAND_M	Mixed conifer forest	X
CHCU	CHCU_S	Sandy loam upland grassland and shrubland	-
GLCA	GLCA_A*	Desert shallow sandy loam shadscale	-
GLCA	GLCA_D	Desert sand grassland and shrubland	-
GRCA	GRCA_M	Mixed conifer forest	X
GRCA	GRCA_P	Pinyon-juniper woodland	X
MEVE	MEVE_L	Loamy mesa-top pinyon-juniper woodland	C
MEVE	MEVE_S	Shallow loamy mesa-top pinyon-juniper woodland	C
PEFO	PEFO_C	Clayey fan grassland and shrubland	C
PEFO	PEFO_S	Sandy loam upland grassland and shrubland	C
PETR	PETR_P	Malpais grassland and shrubland	-
WACA	WACA_P	Ponderosa pine woodland	-
WUPA	WUPA_L	Volcanic upland grassland and shrubland	C
WUPA	WUPA_S	Loamy upland grassland and shrubland	C

*GLCA_A is a potential ecosystem for upland monitoring but has not yet been established.

4.2 Selecting target cells in upland ecosystems.

For land surface phenology monitoring, SCPN is initially choosing those upland ecosystems that the network is also monitoring with ground-based plots as part of the integrated upland vegetation and bird community monitoring protocols. The upland vegetation and bird community ecosystems were chosen for monitoring based on park priorities, ecosystem extent, and logistical sampling considerations (DeCoster et al. 2012, Holmes et al. 2015).

The upland vegetation and bird community monitoring ecosystem inference frames were generally based on the system of ecological site designations that is maintained by the Natural Resources Conservation Service. An ecological site is defined as land with specific physical characteristics that differs from other kinds of land in its ability to produce a distinctive kind and amount of vegetation (USDA 2003). Ecological sites have associated state and transition models, providing a conceptual framework for interpreting change. These have the advantage of not being limited by political or land management boundaries, while still being associated with map units within SSURGO (Soil Survey

Geographic Database), which is the finest scale soil-mapping program in the United States. Individual SSURGO map units may contain multiple ecological sites. SSURGO databases provide map unit spatial boundaries as well as estimated proportions of the percent cover of each ecological site within a map unit.

MODIS data for target upland ecosystems can be aggregated or summarized in multiple ways. Temporal aggregations can provide maps of peak NDVI values during a particular season or year. Spatial aggregations can provide summary information about the ecosystem as a whole. For the SCPN phenology protocol, it is useful to calculate aggregate spatial statistics for an area that roughly corresponds to the part of the ecosystem that is being monitored through ground-based monitoring (i.e. the inference frame of the upland monitoring protocol). This lets us make comparisons between ground-based, species-specific data and satellite-based phenology patterns. Using inference frames can also be useful because in the process of developing them, SCPN staff excluded burned areas, steep slopes, and areas near roads that are likely to be significantly different.

In many park units, SCPN ground-based monitoring is restricted to a portion of the ecosystem because it would be logistically difficult to monitor the entire ecosystem. For those ecosystems, we can display maps of temporal statistics (e.g. annual peak NDVI) across the entire target ecosystem within the park to show how areas not covered by ground-based monitoring are responding.

Because we want to provide ecosystem-wide summary statistics as well as mapped summary statistics, we can use two general methods for selecting target MODIS cells for ecosystem analysis (Table 1.5). The SSURGO-based method uses SSURGO datasets directly; the inference frame-based method uses SCPN inference frames from the upland monitoring protocols, which are themselves generally based on SSURGO datasets that have been modified (DeCoster et al. 2012, Appendix A). For many ecosystems, both methods are used—inference frame methods are used to calculate ecosystem-level statistics that can be compared to ground-monitoring data, while the SSURGO-based methods are used to map phenological statistics across the entire ecosystem.

Table 1.5. Methods used to select sets of MODIS cells for each SCPN target ecosystem. SS refers to SSURGO-based method (section 4.2.1); IF refers to inference frame-based method (section 4.2.2); NA indicates ecosystems excluded from phenology monitoring at this time because of problems with winter-peaking NDVI (section 3.2).

Ecosystem Identifier	Mapped NDVI display	Ecosystem level NDVI statistics	Comments
AZRU_A	SS	SS	-
BAND_M	Postpone	Postpone	Ecosystem may not be based on ecological sites. Major fires in park make use of SSURGO difficult.
BAND_P	NA	NA	Excluded because of problems with NDVI in pinyon-juniper and ponderosa ecosystems.

Table 1.5. (*continued*) Methods used to select sets of MODIS cells for each SCPN target ecosystem. SS refers to SSURGO-based method (section 4.2.1); IF refers to inference frame-based method (section 4.2.2); NA indicates ecosystems excluded from phenology monitoring at this time because of problems with winter-peaking NDVI (section 3.2).

Ecosystem Identifier	Mapped NDVI display	Ecosystem level NDVI statistics	Comments
CHCU_S	SS	SS	We use a park-specific non-standard SSURGO product to match the product used for ground-based monitoring.
GLCA_A	SS	SS	Establishment of ground-based monitoring has not yet begun. May subdivide into geographic areas.
GLCA_D east	SS	SS	Grouped into east central and west because of large geographic extent.
GLCA_D central	SS	SS	Grouped into east central and west because of large geographic extent.
GLCA_D west	SS	SS	Grouped into east central and west because of large geographic extent.
GRCA_M	IF	IF	Major fires in park make use of SSURGO difficult.
GRCA_P	NA	NA	Excluded because of problems with NDVI in pinyon-juniper and ponderosa ecosystems.
MEVE_L	NA	NA	Excluded because of problems with NDVI in pinyon-juniper and ponderosa ecosystems.
MEVE_S	NA	NA	Excluded because of problems with NDVI in pinyon-juniper and ponderosa ecosystems.
PEFO_C	SS	IF	Will group based on recent park expansion area.
PEFO_S	SS	IF	Will group based on recent park expansion area.
PETR_P	SS	SS	A small area to the northeast is not represented. This is the best tradeoff because we expect an expansion of ground-based monitoring plots and inference frame.
WACA_P	NA	NA	Excluded because of problems with NDVI in pinyon-juniper and ponderosa ecosystems.
WUPA_L	SS	IF	-
WUPA_S	SS	SS?	Probably use SSURGO for mapped areas to show full spatial variability in park. Decide whether SCPN area is substantially different.

4.2.1 SSURGO-based method of target cell selection

For SSURGO-based methods, we reproject and overlay SSURGO soils map data (typically 10 m gridded data) on the sinusoidally projected MODIS cells boundaries. We then select the MODIS cells that are covered by some threshold of the target SSURGO map unit(s) (Figure 1.7). Target map units were identified for each ecosystem as part of the protocol development process for the upland vegetation monitoring protocol (DeCoster et al. 2012). Similarly, we overlay NPS park unit boundaries on MODIS cell boundaries and select only those cells that completely (or nearly completely) fall within the NPS park unit boundary.

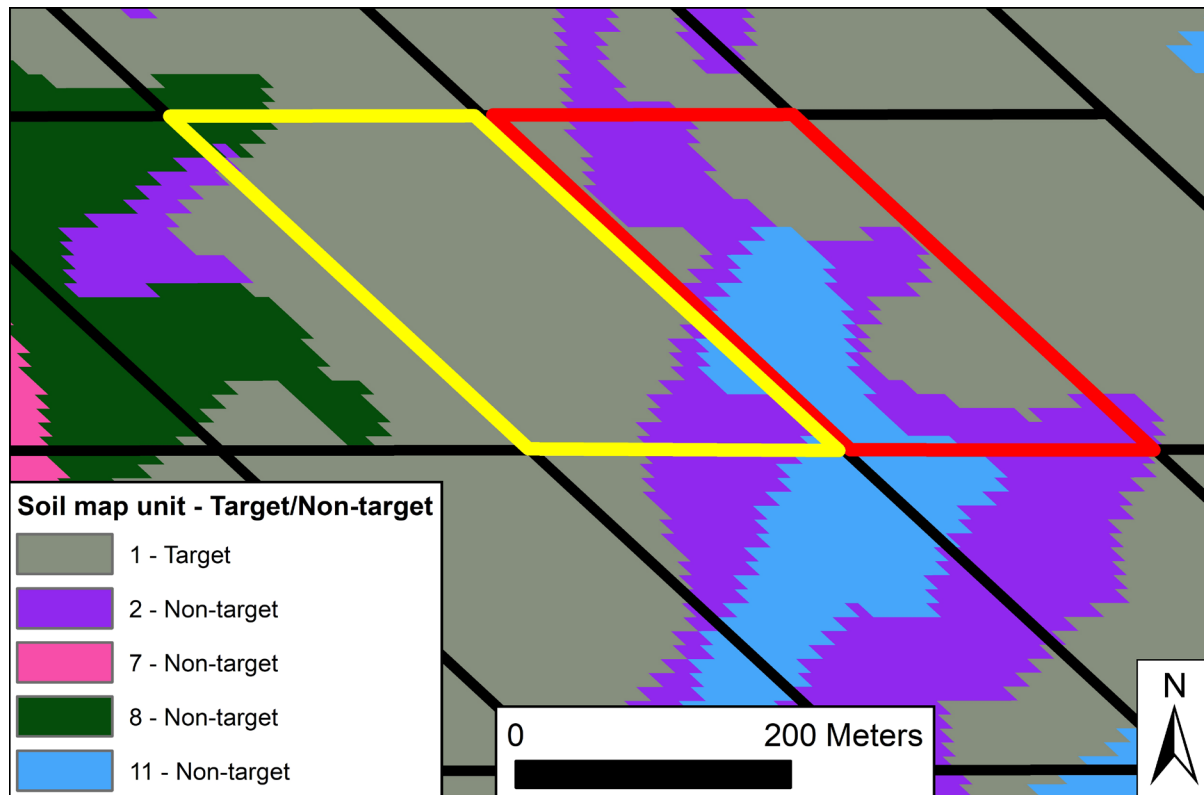


Figure 1.7. Example of how a single MODIS 250 m cell is either included or rejected for target ecological site level analyses. In this case, the yellow highlighted MODIS cell would be included because > 80% of the cell is the target soil map unit. Conversely, the red-highlighted MODIS cell would be rejected because it contains < 80% of the target soil map unit. Note that the shape of individual MODIS cells on the surface of the earth is a rhomboid rather than a square for most commonly used MODIS products.

4.2.2 Inference frame-based method of target cell selection

SSURGO-based methods are not used for most ecosystems with histories of moderate to severe burns (e.g. some pinyon-juniper woodlands and most mixed conifer forests). In upland ecosystems where SSURGO-based methods are not used, we use inference frame-based methods by overlaying the MODIS cell boundaries on the existing inference frame polygons from SCPN ground-based upland vegetation monitoring. We select MODIS cells that are at least 80% covered by the target inference frame. We use upland vegetation monitoring inference frames instead of the upland bird monitoring inference frames because the bird frames form a more restricted subset of the vegetation frames, both in extent and in number of ecosystems monitored (Table 1.4).

4.3 Selecting target cells in riparian ecosystems

SCPN target riparian ecosystems are groups of cells overlapping riparian areas that together provide consistent phenological signals. Riparian ecosystems in the SCPN typically do not cover entire MODIS cells. However, they are often extensive enough that statistics can be used from multiple cells to see consistent phenological patterns. The potential shifting of cell boundaries by up to 50 m among different overflights means that cells are likely to have different proportions of riparian vegetation cover at different times, but with enough cells, the overall pattern of the different

percentile statistics is similar. For riparian systems, reporting a higher percentile NDVI value (e.g. 90%) for the ecosystem is more appropriate than the median value because we are attempting to estimate the riparian signal without mixing from adjacent upland vegetation.

Riparian areas that are too small or have too much shading due to canyon walls will have inconsistent, variable NDVI values that do not correspond to normal ecological phenology patterns. These areas will not be included in analysis.

The shifting cell boundaries coupled with the narrow riparian corridors found in SCPN park units could lead to somewhat lower confidence in the amplitude of the NDVI signal in smaller riparian ecosystems, but should still provide robust data with regard to the timing of riparian greenup and senescence. The timing of greenup and senescence is expected to be a useful indicator of how changing temperatures are affecting the overall growing season length.

Riparian phenology signals are particularly useful in dryland systems for analyzing climate change-related trends in the timing of the start-of-growing-season, and the length-of-growing-season. This is because the confounding factor of water limitation is removed. Non-water limited riparian areas provide a clearer signal of the temperature-driven growing season start and end than does the adjacent upland vegetation. Vegetation in non-water-limited riparian areas has access to water, typically groundwater in shallow alluvial aquifers, throughout the year.

In water-limited riparian ecosystems, vegetation may have access to water only seasonally or intermittently. In water-limited riparian ecosystems, we would typically see decreases in NDVI during the growing season, as some vegetation loses access to water. NDVI may or may not increase again later in the season in response to monsoon rain. In water-limited riparian ecosystems, it may still be possible to determine a temperature-driven start of season, and patterns of dryness through the season may be useful to understand trends in water availability through time.

4.3.1 Target cell selection method for riparian ecosystems

Cell centers representing riparian ecosystems are selected by hand using a combination of high-resolution aerial photos and overlays of late summer NDVI grids from multiple years. Cells influenced by riparian vegetation appear substantially 'greener' than adjacent upland vegetation. Areas within the high water boundaries of reservoirs are not included because of potential NDVI signal alteration from inundation by the reservoir.

Once the cells are chosen, data from the riparian cells are processed and the data are reviewed to determine if the phenological patterns follow reasonable ecological patterns. NDVI should not rapidly increase or decrease beyond what could be reasonably expected, and the year-to-year patterns between nearby riparian systems should be similar. We expect that extreme flash flooding in individual systems will create a disturbance-recovery pattern in the data in some years.

4.4 Future expansion of analysis areas

In the future, after becoming familiar with the patterns and necessary quality screening steps associated with the first set of target areas, we will consider expanding our analysis areas to include

- A larger set of ecosystems based on ecological sites within network parks that will be chosen based on the typical slopes, total area, and consistency of the ecological site. The consistency will be evaluated using the estimated percent cover of the ecological site within individual soil map units.
- A complementary set of ecosystems based on ecological sites that are adjacent to parks, focusing on ecological sites that also have substantial coverage within the park to provide a means of comparison.
- Analysis areas whose boundaries are identified and grouped by phenological data characteristics. This allows the characteristics of the data to drive the definitions of the grouping areas and may provide greater accuracy than traditional methods based on GIS vegetation and soils mapping datasets that often have large associated errors.

For these expanded areas, the questions or hypotheses that arise from the satellite phenology data can act as triggers for further investigation that could be accomplished using either ground-based information or higher resolution historical aerial or satellite imagery.

4.4.1 Considerations when adding new areas

In the future, target cell lists can be created on-demand for any area of interest. When identifying the target area, an ecologist and spatial analyst should first consider the nature of the target area and any issues that might require extra pre-screening or extra statistical treatments to remove outliers, such as

- Areas with steep topography, where the steep terrain could affect reflectance properties, and where shading would be more common.
- Areas with strong signals from adjacent land or inclusions within the dominant mapped land type, such as riparian corridors, sewage lagoons, retention structures, disturbed areas along roadsides that receive excess runoff, or locations next to steep topography. In addition to the issue of including different vegetation types in cells, there may be variable inclusion through time: MODIS cell boundaries theoretically do not shift through time, but the estimated cell registration error for MODIS products is up to 50 m.
- Areas with substantially different land use or disturbance histories.
- Areas with substantial areas that are misclassified. Most vegetation, soils, geology and disturbance maps available at this time have >20% error rates.

We currently deal with these types of problems using a combination of screening, where possible (e.g. we remove moderately to heavily burned areas from the analysis area), and by using percentile values for reporting—using medians instead of means and interquartile ranges to characterize ecosystems rather than using maximum and minimum values (see section 5.1.2).

4.5 Assumptions of similarity for ecosystems

When choosing cells for grouping, it is important to be aware of factors that could violate assumptions of similarity within the ecosystem. These include differences in

- dominant vegetation
- geology
- roads or structures
- slope and aspect
- disturbance history
- current and past land management differences (e.g. cattle grazing, forest thinning, and exotic species removal)

These factors can affect both single cell calculations if there is high variability within a single cell, as well as multi-cell aggregations. For both inference frame and SSURGO- based methods, the ecosystem areas may be adjusted to remove (Table 1.6) or to separately group areas that are expected to be substantially different (see section 5.1.3).

Table 1.6. Example of screening criteria for developing target cell selections from inference frames and from SSURGO data. Inference frame development described in this table is done as part of the integrated upland vegetation monitoring protocol (DeCoster et al. 2012) and is detailed in Appendix A of that protocol.

Removal Condition	Criteria used to select target cells	
	Ground based inference frame development	SSURGO-based
Map unit selection	A soil map unit is typically retained if a target ecological site comprises $\geq 80\%$ of the map unit. Some parks have lower thresholds when the target ecosystem did not occur over large areas $>80\%$ of a map unit.	Follows the same standards for target map unit selection from ground-based monitoring.
Ecological site	Soils at each plot are checked for consistency with ecological site description. The resulting inference frame is adjusted as part of the integrated upland protocol.	Retained MODIS cells where $\geq 80\%$ of the cell falls within the target map unit(s) within the park.
Roads or other infrastructure (developed areas, ruins, buildings, structures)	Interstate highways, removed area within a 200 m buffer. For other features including non-interstate road and buildings typically removed areas within a 100 m buffer.	Not separated. The most affected park is PEFO, where the width of the interstate, including vegetated roadside margins, is ~ 60 m. (SCPN visual estimation, 2019).

Steep slope	Ecological sites characterized by steep slopes are already generally excluded. Map unit areas were further screened to remove any areas with steep slopes.	Ecological sites characterized by steep slopes are already generally excluded. Steep slopes may occur associated with non-target soil components of map units. No further exclusions are made.
Burned (forest and pinyon-juniper ecosystems only)	Removed moderate to high severity burn categories in consultation with park staff. Eventually, burned areas may be analyzed separately.	For now, not using SSURGO frames in ecosystems with significant burn areas (GRCA_M, MEVE_L, MEVE_S, BAND_P). Eventually burned areas may be analyzed separately using fire perimeter and burn severity datasets.
Undergone fuels treatments	Variable by park and treatment plan, but typically a 50 m buffer. Generally, we excluded small areas that were significantly different from the majority of the ecosystem. In BAND_P, most of the ecosystem was treated and so treatment areas were not excluded.	Not separated.
Research Plots	Variable by consultation with park staff, typically 50 m buffer.	Not separated.
Inaccessible	Retain areas within ~2 hours walking distance (one-way).	Not applicable.

5 Data Summarization and Communication

SCPN is using three main types of land surface phenology data summarization:

- Current phenological conditions using ecosystem-level NDVI data, updated weekly
- Summaries of annual data and period of record data using aggregated annual statistics and/or maps of annual statistics
- Change and trend analysis, either standalone or integrated with other physical or biological information.

The current conditions and summaries may be provided as reports or as online datasets and figures. More detailed change and trend analyses will be provided as reports.

5.1 Aggregation and annual phenological statistics

SCPN will report phenological data using a combination of weekly graphical and tabular web data reporting, and less frequent synthesis reports that will look at multiyear patterns of phenology and associated environmental drivers. SCPN will calculate these statistics using R scripts. This process will be described in more detail in another SOP (in development).

Initially SCPN is reporting a conservative set of phenological statistics for each cell and for each aggregate grouping. These include

- peak spring NDVI (March-June)
- timing of peak spring NDVI
- peak monsoon season NDVI (July-October)
- timing of peak monsoon season NDVI
- annual peak NDVI
- timing of annual peak NDVI
- mapped views showing the spatial patterns of all of the above data
- anomaly measures of each of the above data against the average value for that cell or ecosystem for the period of record.

5.1.1 Start and end of season statistics for upland ecosystems

Because of difficulties in determining meaningful start and end of season in dryland systems, we are not calculating those statistics. Multiple methods are available for calculating start and end of season. However, we have found that

- Single threshold values are inappropriate to use because of year-to-year variability.
- Percent-of-amplitude statistics are difficult to use because in dry years the start and end of season are artificially early and late because of the lowered threshold needed to exceed a percent amplitude threshold.
- Curve inflection points or similar methods may be useful, however the multiple peaks that can occur in dryland system make these more complicated to use.

5.1.2 Median values for aggregated statistics

Accurate calculation of MODIS statistics depends on the accuracy of the data used for grouping. Most park-scale or larger soil and vegetation maps have significant error rates, often in the range of 20-40%. Two ways to adjust for imperfect data are

- 1) Use percentile statistics, such as the median, 25th, and 75th percentiles for all aggregate values. Using median values prevents extreme values that may be outliers from influencing ecosystem statistics. We may also use the interquartile (25th to 75th percentiles to understand the range of phenological variability within an ecosystem, if we can assume that no more than ¼ of each of the extreme high or low values are non-target cells. SCPN is currently using this method.
- 2) Use patterns within the data to identify appropriate cell groupings and to identify outliers by using automated clustering techniques. This is a valuable strategy because through this process we may

learn more about each ecosystem's phenological patterns and its true spatial extent. These patterns may also be used to inform future vegetation or ecological site mapping.

5.1.3 Subgrouping conditions

In addition to ecosystem designations, it may be appropriate to further group or exclude areas based on geography, disturbance history, and current or past land management practices (Table 1.7).

Table 1.7 Examples of cell subgrouping for MODIS NDVI aggregation. Some ecosystems may have more than one subgroup.

Park	Primary group	Subgrouping 1	Subgrouping 2
PEFO	Ecosystem: Sandy loam upland grassland	Area with different land management history: park area added in 2004.	-
GLCA	Ecosystem: Desert sand shrubland	Geography: park extends for more than 200 km, compare geographic precipitation correlations and group by major areas.	Grazing history within and adjacent to GLCA
GRCA	Ecosystem: Mixed conifer forest	Extend area to include adjacent Kaibab National Forest with the same ecosystem but different land management practices.	Fire history, group burned areas separately

5.1.4 Future phenological statistics

Once the initial reporting process is automated and complete, we will consider additional phenological statistics to evaluate and report, such as

- start-of-season, end-of-season, and length-of-season for riparian ecosystems, because these statistics are better-defined in riparian ecosystems
- integral (area under the curve) NDVI values for all ecosystems using set periods of the year to avoid difficulties with using integrals during a variable and poorly defined growing season
- data-driven aggregate statistics using techniques such as cluster analysis to identify common patterns among cells and to group them based on their phenological behavior

6 Software

The land surface phenology monitoring protocol uses five software packages or tools for data processing (Table 1.8). SCPN does the initial data processing, including quality screening and NDVI calculation, using Google Earth Engine (GEE), but it could also be done using other forms of data download. GEE dramatically increases processing speed and reduces local hardware requirements for speed, RAM, and storage. GEE also allows rapid testing of different methods, and reduces the number of intermediate products.

Once data are exported using GEE, we use R statistical software for further phenology data processing (Table 1.8). The advantages of a workflow based on R include

- Low cost (free).
- In widespread use, with large scientific user community.
- Extensive system of packages for data processing, statistical analysis, and graphing.
- SCPN already uses R for network protocols.
- Script interface allows automated processing.

These advantages outweigh the disadvantage of R not being a dedicated remote sensing data handling program. We use the R-Studio interface to R for most script development and data analysis.

The process of identifying target areas is separate from phenological satellite data processing. As described earlier, target areas are created by integrating geographic data from layers, including park boundary files, SSURGO data, and SCPN inference frames, and may include other layers that would contribute to a target area grouping. To develop target area definitions, SCPN is using a combination of Esri's **ArcGIS for Desktop/ArcGIS Pro** for GIS data handling and **Microsoft SQL Server** for handling the tabular outputs of data intersections. Target areas are expected to be consistent through time, and we have not automated the steps creating them.

Table 1.8. Steps in MODIS data processing and software used to accomplish each step.

Step	Software/Tool	URL
Create definitions of target areas	ArcGIS, SQL Server Management Studio	http://www.esri.com/software/arcgis
Automate processing scripts	Multiple possible, including Python and Windows Task Scheduler	Preinstalled in Microsoft Windows environment. https://www.python.org/
Filter high quality values, calculate NDVI and download MODIS Aqua and Terra data for target ecosystems	Google Earth Engine	https://code.earthengine.google.com/
Smooth Aqua and Terra data using a 15 day median smooth with a minimum of 3 daily values for each 15-day window	R with R-Studio interface	https://www.r-project.org/ and https://www.rstudio.com/
Interpolate missing days using linear interpolation from before and after the missing period.	R with R-Studio interface	https://www.r-project.org/ and https://www.rstudio.com/
Store data in NPS database	Microsoft SQL Server	https://www.microsoft.com/en-us/sql-server/
Summarize and graph data for reporting	R with R-Studio , likely to evolve with reporting needs	https://www.r-project.org/ and https://www.rstudio.com/

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8 Revision History

Provide the following information for each revision made to SOP 1 listed in the Revision History Log. Begin with this, the most current version, and work back through previous versions.

Version: SCPN_Landscape_Phenology_SOP1_20200129

Sections affected:

Changes & reasons:

Approved by:

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The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

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